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Paper Synopsis:

Wargame 2000 is a cutting-edge command and control simulation being developed at the Joint National Test Facility in the United States. This paper describes the development of a Simulated Commander for Wargame 2000. A new requirement for its Theater Air Missile Defense mission is to simulate decision-makers. Although the Synthetic Theater of War project successfully advanced technology in the field of simulated human behavior by creating computer-generated forces, these players were low-echelon forces, rather than high-level decision-makers. The objective of our ongoing work is to evolve existing research to meet Wargame 2000 requirements. Especially challenging requirements include modeling "fog-of-war" effects on decision-makers, and dealing with incomplete, uncertain, and possibly conflicting data.

The focus of our current work is to prototype Patriot Battalion Commander behavior in the execution-monitoring phase of a Theater conflict. The architecture consists of a parallel discrete event simulation framework called SPEEDES with applications consisting of a missile defense model, a battle planner, the Fuzzy CLIPS expert system, and decision algorithms drawn from earlier research. Results of the conceptual prototype are presented to show how this analysis is used to influence the design of WG2K. We discuss progress to date, lessons learned, and future challenges.

Introduction

Wargame 2000 is a cutting-edge command and control simulation; i.e., a human-in control testbed for validating doctrine, being developed at the Joint National Test Facility in the United States. A new requirement for its Theater Air and Missile Defense mission is to simulate decision-makers. Although the Synthetic Theater of War project successfully advanced technology in the field of simulated human behavior by creating computer-generated forces, these players were low-echelon forces, rather than high-level decision-makers. The objective of our ongoing work is to evolve existing research to meet Wargame 2000 requirements. Especially challenging requirements include modeling "fog-of-war" effects on decision-makers, and dealing with incomplete, uncertain, and possibly conflicting data.

The focus of our current work is to prototype Patriot Battalion Commander behavior in the execution-monitoring phase of a Theater conflict. A unique feature of our design methodology is that it is decision-centered: decisions are derived from mission requirements and are supported by displays and algorithms. The architecture consists of a parallel discrete event simulation (PDES) framework called the Synchronous Parallel Environment for Emulation and Discrete Event Simulation (SPEEDES). Applications include a missile defense model, a battle planner, the Fuzzy CLIPS expert system, and decision algorithms drawn from our earlier research. The PDES framework and the formulation of the simulated commander as a swarm of intelligent agents are vital for high performance on a supercomputer.

Performance requirements that stress the resulting architecture are the need to employ up to 50 simulated commanders for system test and to execute the wargame at up to 100 times faster than real time. Results of our conceptual design and demonstration prototype are presented to show how this analysis is used to influence the design of WG2K. We discuss progress to date, lessons learned, and future challenges.

Background

In December 1995, the JNTF commander requested that the Ballistic Missile Defense Advisory Council conduct a review of JNTF computer modernization strategy. The review was conducted in January 1996 and the resulted in a Committee Report that identified broad cultural issues and specific steps to aggressively adopt parallel and distributed versus centralized, single-processor computing approaches. A new improvement and modernization (IM) strategy was developed and packaged as an investment in people and technology. The Technology Insertion Studies and Analysis (TISA) project was initiated in February 1997 and tasked with investigating high-payoff technologies. An initial focus to support WG2K Preliminary Design Review (PDR) in November 1997 provided a conceptual design for the Simulated Commander.

During its first year, TISA research began with trade studies to help choose a PDES framework (SPEEEDES was chosen). We also looked at environments for developing a Simulated Commander (SOAR, ModSAF, Suppressor were evaluated). Decision algorithms from earlier work with potential applicability (a case-based planner for locating battle resources, and a belief network for data fusion). A requirements analysis, based on the WG2K System Specification[i], was also conducted to derive functional, interface and performance requirements. These results were presented at the PDR and provided a foundation for the work presented here.

Requirements

Functional requirements for the WG2K Simulated Commander are summarized in Figure 1. The need for mid echelon decision-making: for example, a Patriot Missile Battalion Commander, and the need for vertical interactions with higher-echelon and lower-echelon players (real or simulated) is apparent. The ability to switch between a simulated and a real commander also needs to be provided. The basis for the initial delivery is a rule-based, but derived requirements point to the need for a variety of algorithms.

Four requirements in the table specify what the Simulated Commander must do. Target prioritization by threat type and launch location exemplifies a decision that is amenable to rule-based algorithms. Perceived data is inherently uncertain and incomplete – this led us to consider Fuzzy CLIPS and belief networks for data fusion. Cognitive functions, such as the ability to recognize and react appropriately (as a human would) in self-defense situations, require rapid decision-making, especially with missile launch scenarios where timelines are short. The simulated commander is required to interact with either an automated or a manual battle manager: in the Theatre Missile Defense (TMD) case, default rules and common sense reasoning may provide solutions.

The realistic environments requirement is the most challenging. Although this is a far-term requirement, the initial formulation must provide extensibility. Decision-making based on attributes such as level of training, morale, fatigue, national resolve, political or religious influences have not yet been demonstrated in command and control simulations. We favor a society of intelligent agents[ii] software paradigm for providing this functionality because it is inherently extensible, matches the Object-Oriented nature of WG2K, and should allow fine-grain partitioning for high-performance computing.

- **Command Level**: Initially, SC will be capable of mid-level command functions, e.g. to construct and generate orders
- **Multi-Echelon Interaction**: Simulated Commander will not initially report to other SCs, but will be extensible to interact at multiple levels
- **Toggled Control**: WG2K will provide a means to switch control of a player position between human control and computer control
- **Rule-Based**: SC decisions will be (initially) based on predefined rule sets
- **Target Prioritization**: SC will be capable of target prioritization based upon target type and launch location
- **Perceived Data**: SC will act only on perceived data that is available to live counterpart
- **Cognitive Functions**: SC will be capable of recognizing and reacting appropriately in self-defense situations
- **Capabilities:** SC usually acts on data provided by automated C2 and Battle Management systems, but in some low level TAMD instantiations, the SC will perform some "manual" target prioritization, track fusion, and engagement planning in NMD case, this data will be provided by an automated Battle Manager
- **Realistic Environments**: SC will be extensible to making decisions based on factors such as level of training, morale, fatigue, national resolve, political or religious influences

Figure 1. WG2K Simulated Commander Primary Requirements

Conceptual Design

The overarching philosophy that guided our effort was the concept of a decision-centered methodology (Figure 2.). The mission requirements were translated into a scenario to provide a concrete foundation for understanding and visualizing the TMD domain. In addition to the functional requirements (Figure 1.), quantitative performance requirements (QPRs) were derived – the driving QPR is to perform a TMD mission with 50 simulated commanders at 100 times real time. Requirements were then allocated to processes: we choose the Joint Operational Planning and Execution System[iii] because it is widely used by the United States military. The focus of our effort was the TMD Patriot Missile Battalion Commander – this processing thread is rich enough to provide interesting rules and algorithms for the simulated commander to execute.

Operator decisions (human or simulated) are the most important part of the methodology. Decisions are derived from the processes allocated to a human Patriot Battalion. This keeps the interface between the simulated commander and the battle manager clear! The simulated commander does only what a human would. Displays to the simulated commander exist only to help with decisions; however, we also use displays to characterize the global situation, show inputs to the Patriot Battalion Commander, and to summarize the results of decisions. Displays showing the decision process within the Simulated Commander's "head" - and interactions with other simulated or human players - is more challenging.

Algorithms are derived from the flow down of requirements, processes, decisions and displays. In our previous research, this top-down approach to deriving algorithm needs resulted in a clear mapping between process types and algorithm types; for example, case-based reasoning is excellent for planning processes, expert systems are preferred for mission execution, and belief networks provide data fusion for engagement assessment. Importantly, a fancy algorithm is not a solution in search of a problem!

The decision paradigm employed is that a decision is a state transition from a current state to a future state according to a plan. Current states, plans, and future states may be uncertain. Three advantages of this view of decisions are:

- State transition diagram is a staple of object-oriented design.
- Types of decisions map cleanly to types of state-transitions - and suggest useful algorithms.
- Uncertainty is represented explicitly in the decision-making process.

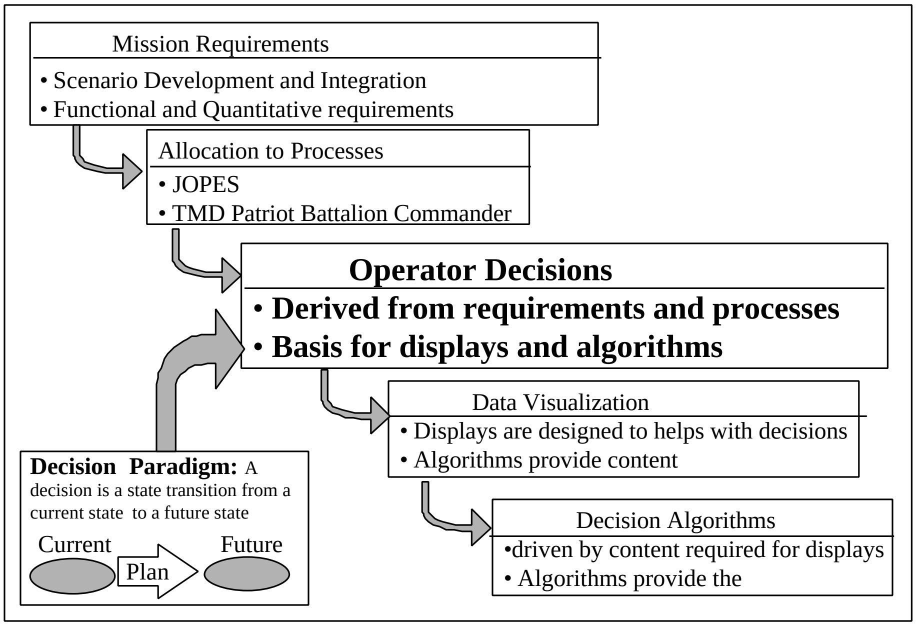


Figure 2. Decision-Centered Methodology

Agent-oriented design[iv] is a generalization of object-oriented design that overcomes many limitations of direct manipulation interfaces (Figure 3.). The biggest advantage of an agent-oriented approach for the simulated commander is scalability: we estimate that up to 50 players at up to 100 times real-time may require WG2K execution on 32 or more processors. Additionally, the simulated commander is a substitute for a human in a discrete-event simulation, and event-driven actions rather than user interaction is essential. Finally, future functionality will require machine learning, which is a feature of the agent-oriented approach

Technology Assessment

Typical Limitations of Direct Manipulation Interfaces	Advantages of Agent-Oriented Approach
• Large problem spaces scale poorly	• Scaleability
• Actions rely on immediate user interaction	• Scheduled or event-driven actions
• No composition	• Abstraction and delegation
• Rigidity	• Flexibility and opportunism
• Functional Orientation	• Task Orientation
• No improvement in behavior	• Adaptive functionality

Figure 3. Advantages of Intelligent Agents

Prototype Development Architecture

The prototype testbed at the JNTF for developing the Simulated Commander is shown in Figure 4. The hardware, operating system, and framework (Silicon Graphics shared memory computer running the IRIX operating system and the SPEEDES framework) are the same as the WG2K development environment. SPEEDES provides the event synchronization and data distribution management utilities to run discrete event simulations in parallel. The SPEEDES environment contains a display interface for situation awareness that we upgraded to OpenGL for portability.

SPEEDES also contains low-fidelity models of threats, weapons, sensors and a battle planner developed by Los Alamos National Laboratory. Fuzzy CLIPS was obtained from the National Aeronautics and Space Administration (NASA). These Government-Off-The-Shelf (GOTS) applications were used to produce input stimuli to the simulated commander and an expert system for executing rules. Fuzzy CLIPS was also used to call decision algorithms.

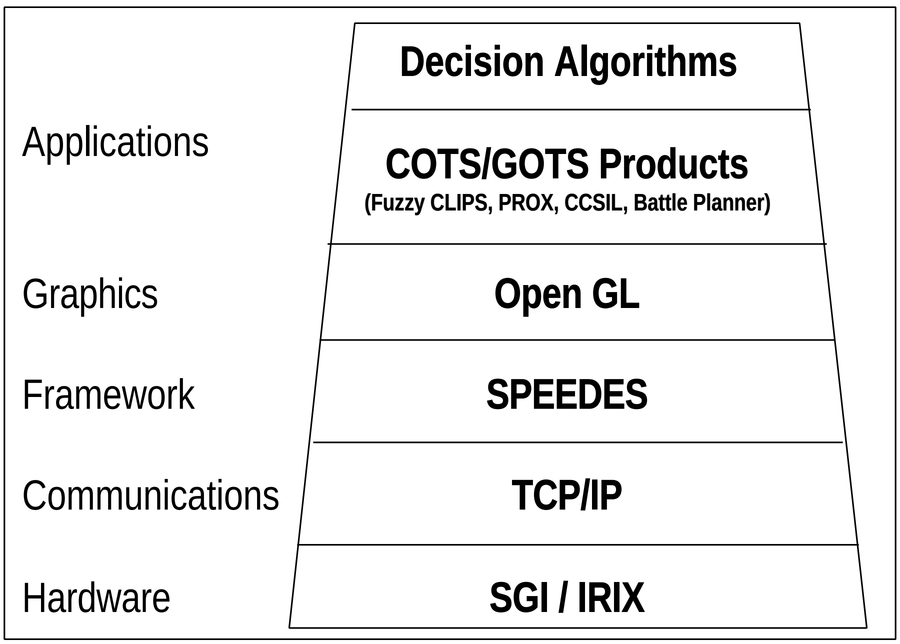


Figure 4. Prototype Development Architecture

The object classes and associations that we modeled are shown in Figure 5. The TMD problem that we portrayed is defensive: a ballistic missile launch is detected by RADARs and space-based infrared systems. Threat detections are reported to a Battle Manager. Data is displayed to a simulated commander who makes decisions about deploying Patriot Missile Interceptors. The Simulated Commander code only interfaces with the Battle Planner code within the Battle Manager composite. Based on these decisions, and in-flight updates on threat trajectories, ground-based kinetic interceptors are launched to intercept enemy ballistic missiles.

Although not explicitly shown, the Simulated commander is involved in all phases of the mission: situation awareness, mission planning, execution monitoring, replanning engagements, assessment, and reconstitution. Our focus is on the execution-monitoring phase.

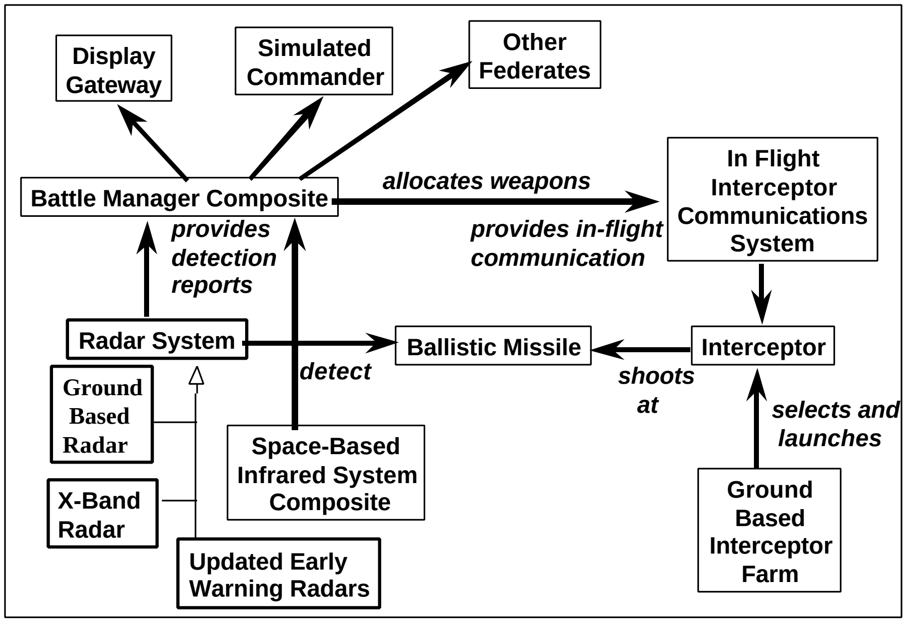


Figure 5. Object-Oriented Design

Fuzzy CLIPS[v] is a NASA software product that provides a comprehensive environment for developing and executing an expert system rule base. Rules were developed to allow a Simulated Commander to make decisions in the execution-monitoring phase of a TMD scenario. These include: Threat Condition (TREATCON) Updates, Rules of Engagement Updates, Mission Objective Updates, and Battle Plan Updates.

The functional model (Figure 6.) provides a SPEEDES-based TMD simulation with realistic (but low-fidelity) physics models that execute in parallel. Simulation time, track data, asset inventories and engagement plans are provided to the battle planner and displayed to a human or simulated commander. Interaction between the Simulated Commander and the Battle Planner are conducted via side-by-side display windows with dialog boxes moving back and forth to "embody" the Simulated Commander decisions and the Battle Planner implementation of the decisions.

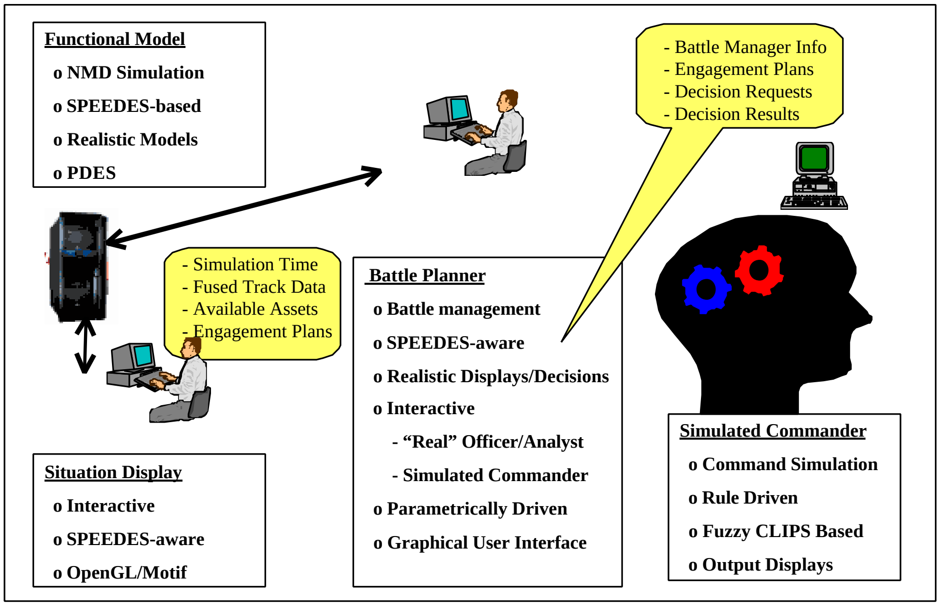


Figure 6. Fuzzy CLIPS Interface to the Battle Planner

Decision Algorithm Execution

We are using Fuzzy CLIPS to execute other decision algorithms; e.g., **IF** decision_type = data_fusion **THEN** CALL belief_network. This hierarchical call structure is convenient and readily extensible.

Two examples of promising decision algorithms to augment Fuzzy CLIPS are discussed.

Long-term planning, based on broad goals, is a difficult problem for rule-based reasoners. The range of possible solutions is an exponential function of the number of decision criteria, which can number 12 or more. The problem of optimally locating transportable resources (Figure 7.) has been solved (in a related domain) using case-based reasoning (CBR). It allows an operator (here, a Simulated Commander) to readily identify locations for resources (here, a Patriot Battery) based on weapon effectiveness calculations. CBR is easily described as a generalization of an engineering trade study: rank pre-stored options according to weighted selection criteria and choose the option, or combination of options, with the highest score.

Need: Operator decision aid to translate broad tasking to a finite set of locations for transportable resources. **Objective**: allow an operator to readily identify locations for transportables that optimize mission effectiveness. **Approach**: Use an enhanced variation of Case Based Reasoning (CBR) that allows astrodynamic calculations to find pre-stored locations that best fit **Theory**: CBR is a powerful advanced computing technology that rapidly searches large solution spaces based on operator selection criteria, weights, and similarity metrics. Our algorithm handles dynamic calculations (innovation) , ranks locations, and provides explanations. **Progress**: Completed prototype algorithms and displays. Driven by a SYBASE relational database containing 55 airbases in Europe, 35 INTELSAT spot beams, etc. Allows map-based planning, and much operator interaction. Used to actually locate a tactical resource.

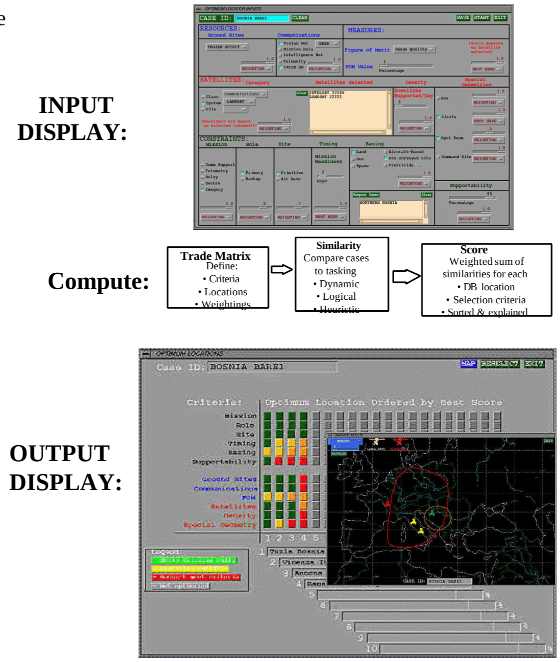
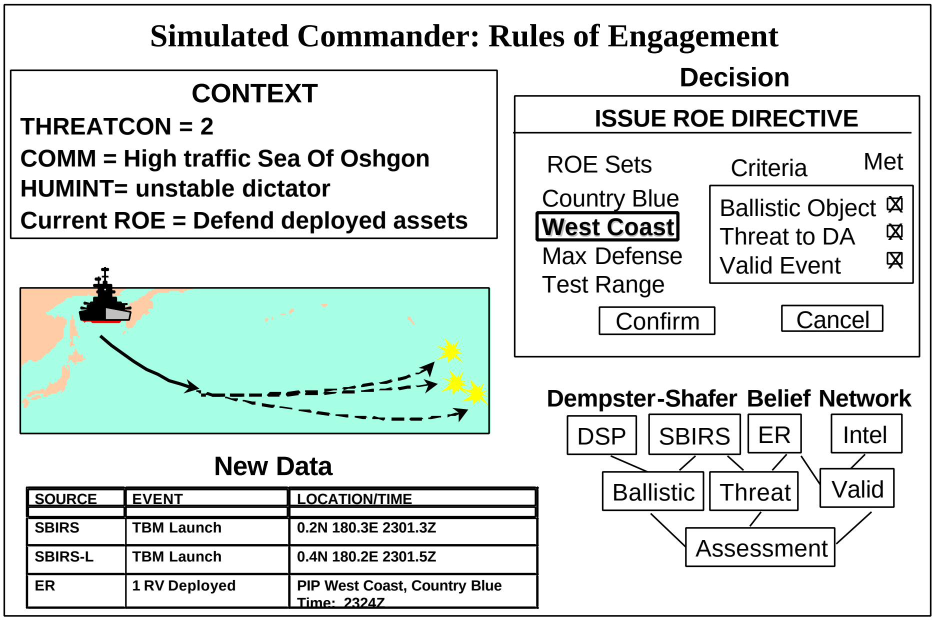


Figure 7. Case Based Reasoning for Planning

Data fusion for engagement assessment (did the Patriot missile intercept the target?) is another problem that is not conveniently solved using expert systems. Perceived data is uncertain, incomplete, and possibly conflicting – and the appropriate rule may not "fire" at the appropriate time! In risky decision-making, two factors are important: confidence and plausibility. To account for these two parameters in an intuitively satisfying way, we have successfully built a Dempster-Shafer Belief Network[vi]. For the TMD problem, the context for data fusion (Figure 8.) is data arriving asynchronously. To update the Rules of Engagement (ROEs), the Simulated Commander must fuse incoming data with the currently perceived situation and issue a new directive as appropriate. Raw data (DSP, SBIRS, XBR, Intel) updates indicators in the middle layer (Ballistic, Threat, Valid) of the belief network, and forms outcomes (Assessments) in the lower level. These are thresholded based on rules to produce a decision.



SOURCE	EVENT	LOCATION/TIME
SBIRS	TBM Launch	0.2N 180.3E 2301.3Z
SBIRS-L	TBM Launch	0.4N 180.2E 2301.5Z
ER	1 RV Deployed	PIP West Coast, Country Blue Time: 2324Z

Figure 8. Belief Networks for Data Fusion

Progress Summary:

Based on WG2K requirements, a conceptual design for a Simulated Commander has been completed. The agent-oriented design relies on fuzzy rules initially and is extensible to a variety of algorithms. The methodology is decision-centered and defines a decision as a state transition for a current state to a desired state, based on a plan. Use of GOTS products allows parallel processing (scalable), provides extensibility, and tackles a realistic TMD scenario. Decision algorithms are called from the Fuzzy CLIPS expert system. We favor case-based reasoning for planning and belief networks for data fusion. We have integrated the collection of hardware and software to produce a prototype testbed with a simulated commander making decisions based on a TMD scenario driven by realistic wargaming models.

Many other artificial intelligence methods have been analyzed, prototyped, and assessed (Figure 8.) for applicability to our task. For example, case-based reasoning is a good for planning, because we already have cases for human commanders and previous wargames. On the other hand, operations research may be good for scheduling, but is too inflexible for modeling human decision-making.

Planning and Assessment Techniques

UTILITY	Planning	Visualization	Data Fusion	Learning	Reasoning
Effective	Case Based	Map-Based	Belief Nets	Rule Based	Heuristic
		Animation			
↑	Genetic Algorithms	Learning Agents	Heuristic	Case Based	Case Based
U T I L I T Y		Hypertext Markup	Templating	Fuzzy Logic	Optimal Policy
	Constraint Satisfaction	Intelligent Multimedia Interfaces	Classical Statistics	Genetic Algorithms	Fuzzy Logic
↓	Simulation	Virtual Reality Modeling			
Ineffective	Operations Research	Virtual Reality	Rule Induction	Neural Nets	Rule Based

Figure 9. Assessment of Decision Algorithms

Future Directions:

In order to evolve the current rudimentary simulated commander to satisfy the "extensibility" requirements of WG2K, many challenges (Figure 10.) remain. For example, representation of the human decision process, especially for modeling "fog-of-war" is the most difficult – common sense is elusive.

Another challenge is to provide scalability for high performance throughput in processing decisions for 50 simulated commanders interacting at up to 100 times real time. Vector processing within the parallel simulation is an option that we are exploring.

Topic	Barriers	Solutions	Risk	Rationale
Search	NP hard	Genetic Algorithms	Low	10 - 100 fielded applications
Real Time Ops	Short Suspense	Case-Based Reasoning	Low	Commercial Products
Expert Systems	Brittle	Neuro-Fuzzy Logic	Low	Japanese Research
Uncertainty	Acceptance	D-S * Belief Networks	Low	Bayesian Nets progress
KDD**	Terabytes	Search Engines	Med	Data must be "clean"
Statistics	Assumptions	belief based	Low	More intuitive vs classical
Scheduling	Reuse	repair	Med	Case-Based Planning
SW that learns	Agents	Agent Builder	Med	Agentware.com (product)
Representation	Ontology	narrow domains	High	Common sense is elusive

* Dempster-Shafer Theory of Uncertain Reasoning gives intuitively satisfying results
** Knowledge Discovery in Databases

Figure 10. Future Challenges

[i] Wargame 20000 Software System Specification
[ii] Minsky,M. The Society of Mind, First Touchstone Edition, 1988.
[iii] Joint Operational Planning and Execution System (JOPES) Planning Policies and Procedure, Volume 1, 4 August 1993.
[iv] Knapik, M. and Johnson, J., Developing Intelligent Agents for Distributed Systems, McGraw-Hill, 1998.
[v] CLIPS Reference Manual, Volume I, Basic Programming Guide, Version 6.05, November 1st 1997.
[vi] Pearl, J., Probalistic Reasoning in Intelligent Systems: Networks of Plausible Inference, Morgan Kaufmann, 1988.